DYNAMIC SIMULATION OF PROCESSES IN THE SOIL UNDER GROWING ROW-CROPS: RHIZOS

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ABSTRACT

Several processes occur simultaneously in the soil under growing row crops. If these processes were isolated and occured independently, the prediction of their behavior would not be so difficult. But the processes interact--each process affect several others. Included in these processes is root growth, which depends on conditions within the root zone and on activity in the aerial portion of the crop. The spatial and temporal distribution of roots affects the pattern of water and nutrient uptake. Consequent root growth is affected by the resultant stresses, and a feedback loop is clearly visible.

The several processes have combined in a dynamic computer simulation using two-dimensional geometry. Included are root growth, water and nitrate uptake, consequent redistribution of water and nitrate within the profile, mineralization of nitrogen, evaporation from the soil surface, and the heating and cooling of the soil profile response of several variables describing the state of the system is predicted from the climate, the photosynthate supply, and soil physical characteristics.

INTRODUCTION

The farm manager typically makes decisions on two time frames--annually and daily. On an annual basis he collects as much information as possible on inputs such as costs of seed, fertilizers, etc., future prices for his products, and the availability of labor, rental land, and capital. Then he makes decisions concerning allocation of those resources for the following growing season. He answers questions such as how many acres of cotton to plant, how much machinery to buy, how much extra land to rent, and how much money to borrow in such a way as to optimize his net return.

On a daily basis a manager makes decisions as to cultural management practices based on such inputs as status of his crops and pests, current and expected weather, machinery and labor requirements and availability. Generally speaking, daily cultural management decisions are based on the expected economic return resulting from the practice compared to the cost of the practice. For example, irrigation of a cotton crop on 7 August would be self-defeating if the cost of applying the irrigation exceeded the additional expected return at the end of the season as a result of the irrigation. (Allen and Lambert, 1971) Similar statements could be made regarding cultivation, insecticides, herbicides, and even the harvesting process itself. In order to make an objective decision involving a given crop, it is necessary to quantitatively predict the marketable yield with and without implementation of the practice. Farmers of the future will do so by computer simulation.

Questions often arise in agriculture concerning the effects and advisability of certain possible genetic manipulations. For example, what would be the effect of a different fruiting pattern on soybeans? Would it be advisable to increase the number of cotton bolls set on a plant? Is it possible that genetic material with fruit bracts which discourage egg laying by the female boll weevil can have as high yield as conventional varieties? This type of question is easier to answer by computer simulation than by traditional field experimentation. Alteration of the affected parameters in the simulation will indicate the results of the genetic manipulation. See Jenkins et al (1971) for a typical approach to such question.

A good researcher is constantly asking himself questions about where and how he can make the most contribution in his chosen area of research. He usually makes a subjective decision based on reading a portion (rather than all, of necessity) of the literature in the field, talking with his colleagues, and thinking about what has been and is being done in the field. Dynamic computer simulations of crop growth and yield have several advantages which aid in the choice of experiments. A composite picture of all known applicable knowledge concerning the species and its behavior is developed during the course of a computer simulation project. For example, a dynamic simulation of soybean growth and yield will utilize existing knowledge regarding such processes as photosynthesis, respiration, translocation, fruiting morphology, water uptake by roots, nodulation and nitrification. At present many information voids exist in the physiological, morphological, and even the anatomical details necessary to ultimately simulate a soybean crop. These voids are prime areas for immediate attack by laboratory and field crop physiologists. If the data and relationships which a given researcher is developing are not necessary to describe the quantitative growth and yield of the crop, the question might well be raised, "Of what value is the research?" As new applicable quantitative information becomes available, it can be incorporated into the simulation. Cooperative research projects are being managed in this way. (Southern Region Cooperative Project No. 107, 1975).

Dynamic computer simulations of crop growth and yield have been, and are being, developed for the three reasons above: decision making in (1) cultural practices, (2) genetic modification, (3) research direction and coordination.

Several species of crops have been simulated. Duncan (1973, 1976) has simulated to some degree cotton, maize, peanuts, and soybeans. Stapleton (undated) was an early contributor to cotton simulation. McKinion et al (1974) and more recently Baker et al (1975) have contributed to the simulation of cotton. DeWit et al (1969) simulated the vegetative growth of maize. Holt et al (1975) simulated the vegetative growth of alfalfa. Fick et al (1973) simulated growth of the sugar beet. Curry et al (1975) have begun a simulation of the soybean, and similar efforts on soybeans are underway as part of the project cited above (S107).

Without exception, models developed previously have either ignored the processes occurring below the soil surface or have treated them in a very empirical or parametric manner, rather than making a rational analysis of these processes. None of these models simulates spatial root distribution, water uptake distribution, nutrient uptake or water movement in the soil. Thus there was no unifying and underlying basis for including fertilization, irrigation, cultivation, etc. RHIZOS, a simulation of processes in the rhizosphere, is being developed in an attempt to meet this need. The computer model is modular so that new or better methods or information can be easily incorporated.

THE SIMULATOR RHIZOS

RHIZOS is a dynamic computer simulator of processes in the rhizosphere, including root growth, water and nutrient uptake, and microbiological processes involving nitrogen. The rhizosphere is defined to be the root zone of the crop, i.e. the soil volume occupied by roots. The concepts hypothesized to explain observable phenomena are developed and implemented via a Fortran program, which is modular from two standpoints. (1) Revised views of the processes may easily replace those assumed initially. This is accomplished by the structure of the program, which, utilizes subroutines and named COMMON. (2) The simulator can easily form a module in a row crop simulator because of the interface which has been designed. So far, it has only been included in a cotton crop simulator and all remarks here will apply to that implementation.

This simulator is not complete. Many concepts and approaches can and will be improved. We present here our best estimate of the current state of the science with respect to the phenomena involved. More definitive and accurate data, relationships, concepts or approaches will be installed immediately after acceptance.

The spatial configuration illustrated in Figure 1 describes a soil slab 1 cm thick and perpendicular to the row. An NL x NK matrix of D cm x W cm soil cells fills the plane between the rows, or NK*W spacing, and to the bottom of the rhizosphere or root zone, NL*D deep. The number of layers (NL), number of columns (NK), depth of each soil layer (D), and width of each soil column (W), are treated as variables throughout most of the program. All work hereto has used NL = 20, NK = 20, and D = W = 5.

Each soil cell is assumed to be homogeneous in all respects--water content, temperature, root density, nitrate and ammonium content, and the organic matter components.

The vertical plane under each row is assumed to be impermeable to water and to root growth, which is assumed to occur symmetrically. Thus the root growth of the left row is simulated, and that of the right row is simply a mirror image of the left. No root is allowed to grow more than one row space long horizontally.

Daily time steps are taken throughout the season but certain processes are approximated by shorter time steps, as noted in the narrative of that particular subroutine.

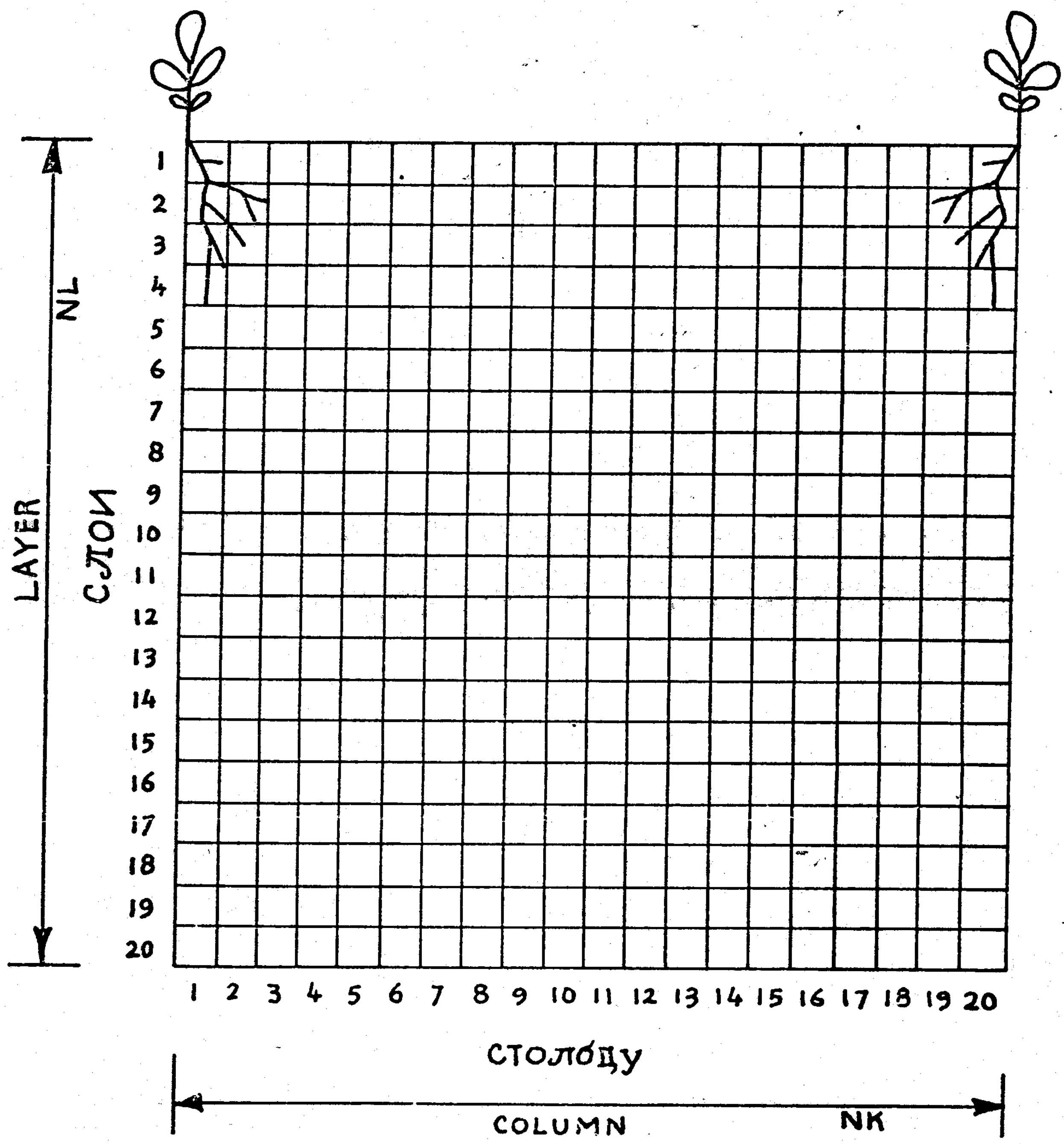


Figure 1. Spatial configuration of RHIZOS.

RHIZOS contains the following subroutines:

RUTGRO: root growth

EVTR: evapotranspiration rate

UPTAKE: uptake of water and nitrate

CAPFLO: capillary flow of water and nitrate

TMPSOL: temperature of soil

NITRIF: nitrification and mineralization

GRAFLO: gravitational flow of water and nitrate

FRTLIZ: fertilization at planting and side dressing

OUT: outputs matrix of certain variables.

The procedure of these subroutines is described in a general sort of way, and the assumptions, procedures and data base are indicated.

Root Growth

Root growth is simulated using a population generator approach: the roots in each cell are treated as a "reproducing" population (Huck, 1974), with the specific rate of reproduction dependent on soil temperature, soil water content and the carbohydrate supply available for root growth.

A three-dimensional matrix of root dry weight (RTWT) contains the roots in each soil cell. The third dimension of this matrix may be represented analogously by a boxcar train of length 3 with root growth contributing to the first car, and the contents shifting down the train to simulate aging of the roots. The first boxcar is assumed to be 3 days long; the second is 9 days long; the third is of undetermined length. The reasons for these particular lengths involve root growth and water uptake characteristics, which are described and which are assumed to be homogeneous within each boxcar. Rather than maintaining identity of each day's growth, which would require a larger array and consequently more computer memory, we move just less than 1/3 (0.3) and

1/9 (0.1) of the contents of boxcar 1 into 2 and 2 into 3 respectively. The only way roots can leave boxcar 3 is by death or sloughing. The assumption is made that only roots 12 days old or younger are capable of growing; i.e. of generating branch roots or extension of the root tip. The root weight capable of growth (RTWTCG) within a given soil cell is obtained by summing the root weights in the first 2 boxcars.

Potential root growth, or potential delta weight of root (PDWRT), within a given soil cell is divided into daytime growth and nighttime growth, and is dependent on moisture stress, soil temperature, and division of the photoperiod into daytime and nighttime according to the equation.

$$PDWRT = RTWTCG \frac{(-0.212+0.016\ T_D)P + (-0.212+0.016\ T_N)\ (24-P)}{24}$$

where T_D = daytime temperature in deg C.

T_N = nighttime temperature

P = photoperiod, in hours

This equation is peculiar to cotton (Gossypium hirsutum), and for lack of better information provides roots with the same exponential growth potential as young bolls. We are currently involved in experimental work to obtain a better estimate of this equation.

As Figure 2 indicates, the sum of the PDWRT's is compared to the supply of carbohydrate available for root growth, a quantity supplied through the interface with the above-ground crop simulator. Potential root growth can occur only if the supply meets the demand; otherwise the total supply is apportioned on the ratio of individual to the total soil cell demands.

The actual increment of root dry weight due to the "population" within a given cell can be added to the cell itself or either all of three adjacent cells, since roots may grow from one cell to another. No upward root growth is allowed,

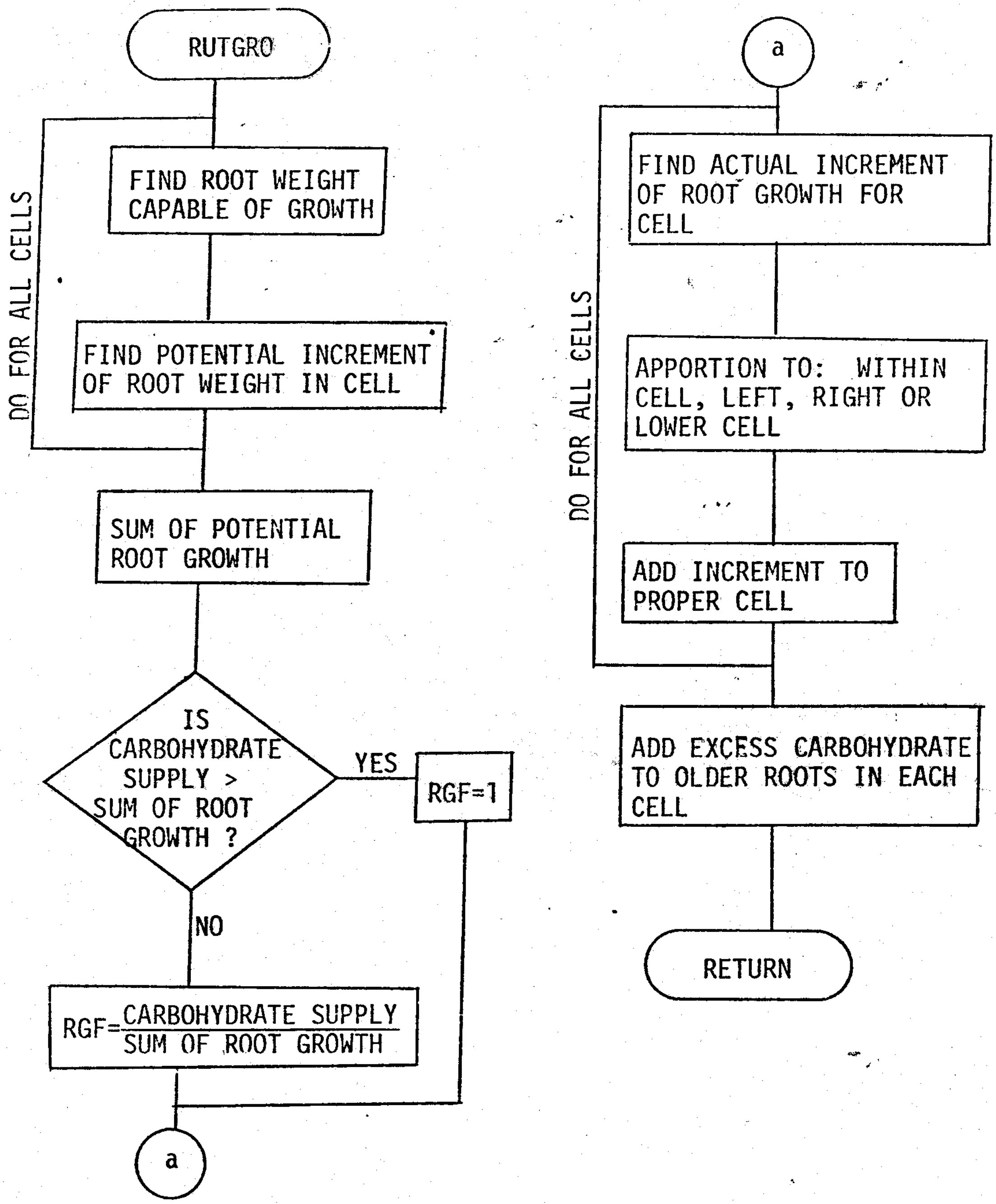


Figure 2. Simplified flow chart for calculation of root growth.

and growth into adjacent cells is not allowed until a threshold length, interpreted as a weight, is exceeded. This assumption accounts for the physical fact that root growth must occur across the cell before entering an adjacent one. To apportion growth in the four possible cells, weighting factors based on water potential are used, on the assumption that roots tend to grow toward areas of higher moisture content. An additional weighting factor reflects the geotropic nature of roots to grow downward. Assumed boundary conditions are that roots cannot cross the vertical plane under the crop row or the horizontal plane beneath the soil profile.

After all root growth is allocated, any excess carbohydrate above that required to meet potential growth demand, is added to roots in the third boxcar to simulate thickening of older roots. This subroutine also simulates the continuous death and sloughing of roots. Sloughing is assumed to be a constant fraction of the weights of roots of all ages.

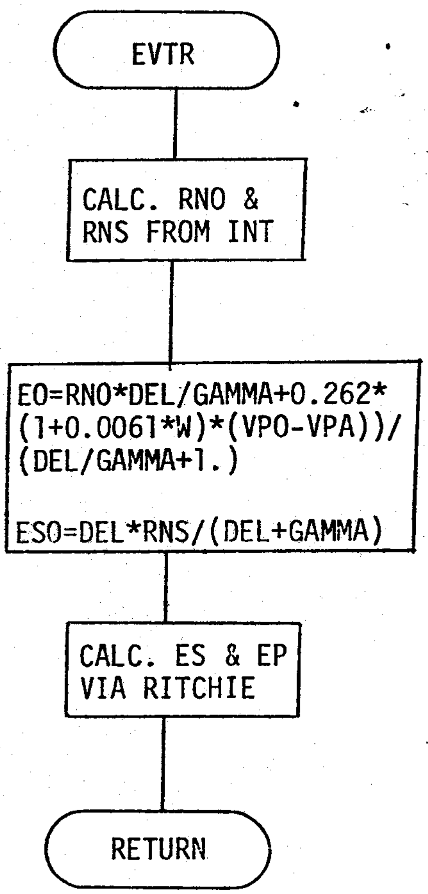
Evapotranspiration

The total water removed daily from the soil by evaporation directly from the soil surface and by transpiration is based on Ritchie's model (1972). See Figure 3.

A departure from Ritchie's use of leaf area index to calculate the radiation intercepted by the crop has been introduced. Instead we use an empirically derived function of plant height and row width. The fraction of the field area actually covered with plant material is called the interception fraction, INT. An overall albedo, λ, is calculated from INT and the crop and soil albedos, λc and λs, respectively:

$$\lambda = INT * \lambda c + (1-INT) * \lambda s$$

The net radiation at the soil surface below the canopy is determined from



RNO-net radiation above canopy

RNS-net radiation at soil surface

INT-interception

EO-potential evaporation rate above plant canopy

ESO-potential evaporation rate from soil surface

EP-evaporation rate from plants, transpiration

ES-evaporation rate from soil surface

DEL-slope of saturation vapor pressure curve

GAMMA-psychrometer constant

VPO-vapor pressure at dry bulb temperature saturation

VPA-vapor pressure at wet bulb temperature

Figure 3. Simplified flow chart for calculation of evapotranspiration.

INT and λs:

$$RN_s = (1-INT) * (1-\lambda s) * RS$$

where RS is the incoming solar radiation.

Once the potential evaporation rates above and below the plant canopy are obtained, Ritchie's model is followed verbatim to calculate soil evaporation. Transpiration is also based on INT rather than leaf area index, with an additional modification for soil water stress. The algorithm for determining the moisture stress reduction factor for transpiration was developed from unpublished data of Baker.

Uptake of Water and Nitrate

The UPTAKE subroutine calculates removal of water from the soil profile by evaporation from the portion of the soil surface unshaded at noon and removes both water and nitrate from the portion of the profile occupied by roots.

Uptake from each soil cell is calculated from:

$$UP_{i,j} = \frac{UPF_{i,j}}{\Sigma\Sigma UPF_{i,j}} T$$

where T is the total transpiration from the profile, $UPF_{i,j}$ is an uptake factor for the i,j cell, calculated by:

$$UPF_{i,j} = RTWTCU_{i,j} * DIFF_{i,j}$$

where RTWTCU is the effective root weight capable of uptake and

$DIFF_{i,j}$ is the soil water diffusivity.

RTWTCU is a composite weight, adjusted for relative permeabilities of roots with respect to age, based on data of Graham (1973). See Figure 4.

All nitrate is assumed to be in complete solution in the soil water and any liquid flux carries with it the dissolved nitrate, including uptake by roots.

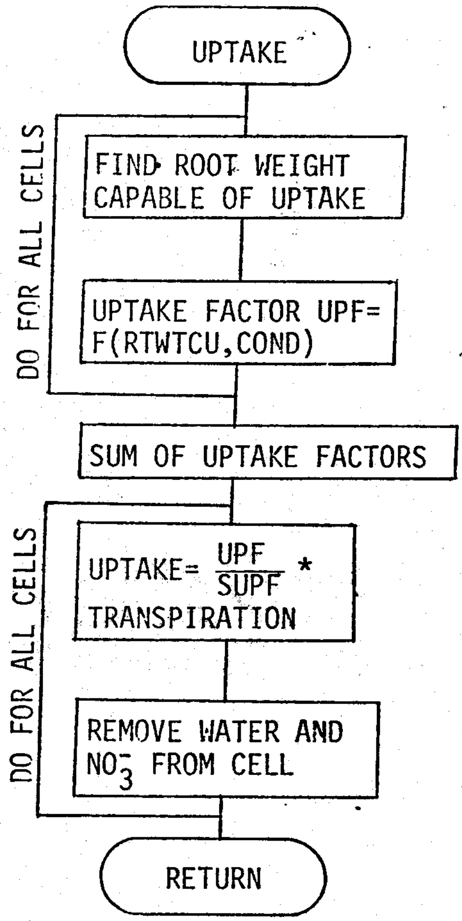


Figure 4. Simplified initial flow chart for calculation of uptake of water and nitrate by roots.

No ammonium is absorbed; it is assumed to be totally adsorbed by soil colloids. The total nitrate absorbed from the profile is calculated so that the aerial portion of the crop simulator can add that amount to the nitrogen budget of the crop.

Capillary Flow of Water and Nitrate

Removal of water from the portion of the soil slab occupied by the roots and from the soil surface causes nonuniform distribution of soil water content and therefore of soil water potential. Driving potential gradients are thus set up which force water to move within the soil capillaries.

The gross flux of water across the boundary between all adjacent pairs of cells is calculated from the moisture content-diffusivity form of Darcy's equation.

$$q + A\ D\ (\theta)\ \frac{\partial \theta}{\partial X}$$

where: A is the area normal to the velocity,

D is the capillary soil water diffusivity,

θ is the volumetric content, and,

X is the space dimension.

An explicit finite difference approximation method is used. Taking direction of flow, boundary conditions and concentrations into account, the net flux of water into each cell is then updated by rectangular integration. See Figure 5.

The boundary condition at the bottom of the soil profile may be handled in any one of several different ways. Currently the bottom layer is assumed to remain at field capacity by capillary flow from below. Thus in the computer program, after capillary redistribution of water has been completed, the bottom soil layer is brought back up to field capacity and any water required to fulfill this condition is accumulated to provide an indication of the amount of subirrigation.

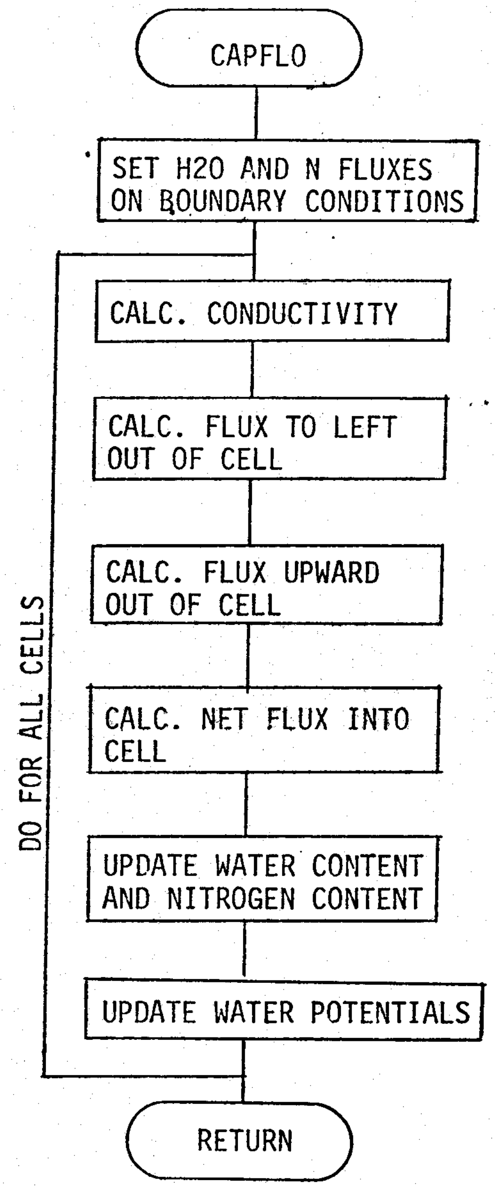


Figure 5. Simplified flow chart for calculation of capillary flow of water and nitrate.

Water flowing from any soil cell is assumed to carry with it nitrate at the concentration of the cell from which the flow occurs. Thus from the gross fluxes of water across the boundaries as calculated above and from the nitrate concentration of the respective cells, the net nitrate fluxes are determined and the cell nitrate contents and concentrations are updated.

Gravitational Flow of Water and Nitrate

Water added to the soil, by rainfall or irrigation, is assumed to move by gravitational force alone. Thus only vertical movement is allowed. As a discrete event, water is added to the upper and successively deeper soil cells of a given column to bring them up to field capacity as long as percolating water is available. Uniform infiltration is assumed. Nitrate is leached downward by mass flow of water: any water leaving a soil cell carries with it nitrate, at the average concentration, into the cell below.

Field capacity is defined as the maximum amount of water a soil can hold against the forces of gravity, due to the capillary surface tension forces. Thus water infiltrating the soil surface wets the soil up to field capacity, with any excess percolating to deeper soil. (See Figure 6).

The reason for the field capacity approach rather than use of a continuous system method of solving the unsaturated flow equations is the size of the time step and the consequent computer time required. Daily time steps are possible using this approach as opposed to time steps in the order of minutes using differential equations.

Soil Temperature Profile

A one-dimensional temperature distribution is determined from daily maximum and minimum air temperatures and solar radiation. The algorithm is a multiple regression equation developed from data of McWhorter and Brooks (1965) combined with an algorithm of Stapleton et al (undated) to place a cosine curve through the

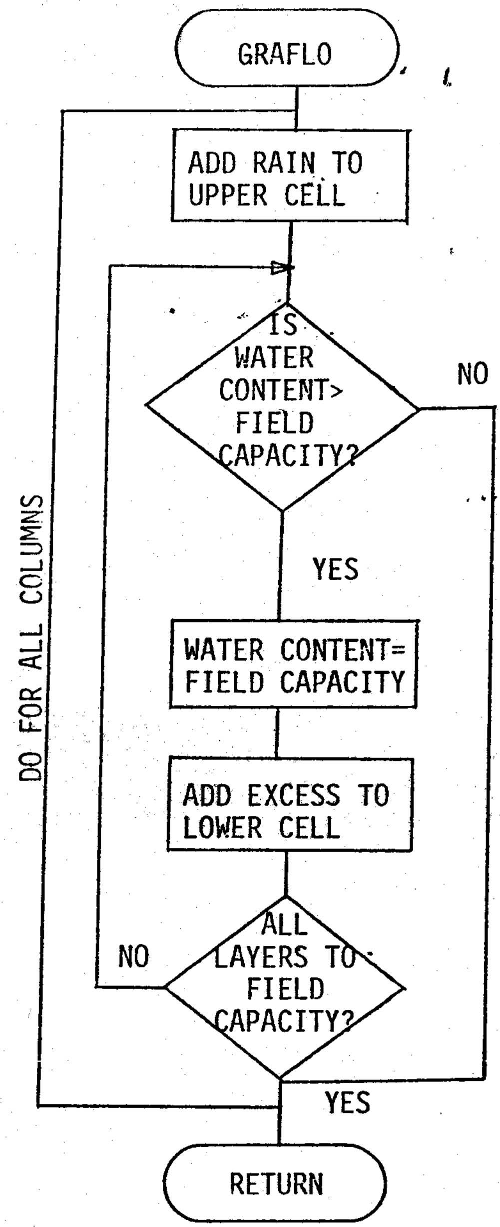


Figure 6. Simplified initial flow chart for calculation of gravity flow of water and nitrate.

predicted minimum, maximum, minimum points to obtain daytime and nighttime average temperatures for each soil layer.

The effects of soil cover, soil water content, and canopy shading are neglected in the calculation of soil temperature. The empirical approach was chosen over more basic approaches, such as a profile heat transfer simulation, for example, because of execution time and accuracy considerations. We believe that the empirical approach required considerably less time and is sufficiently accurate for the desired purposes. Soil temperature is used in the calculation of root growth and of mineralization and nitrification of nitrogen. Temperature errors of 1° C are not believed to be significant in these calculations.

Mineralization and Nitrification

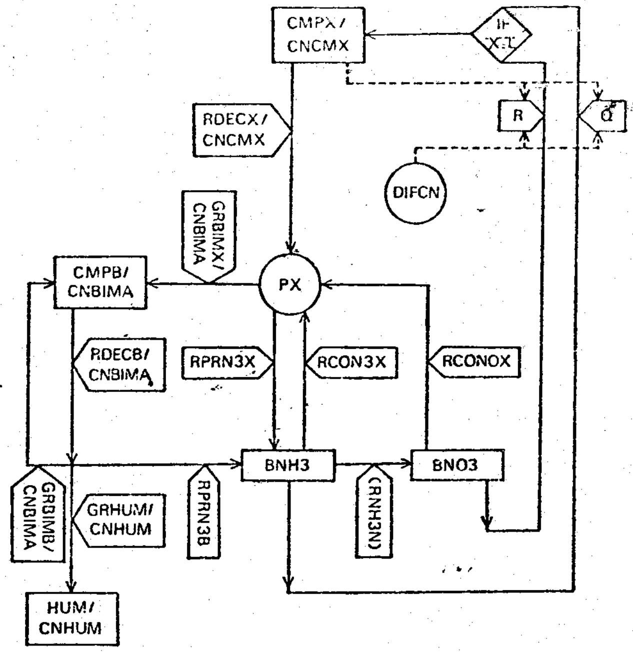
Mineralization of organic nitrogen into ammonium and nitrification of ammonium into nitrate available for root uptake occur within each soil cell and are particularly dependent on soil water content and temperature. These processes are simulated by a Fortran version of the CSMP model of Beek and Frissel (1973). See Figure 7. Volatilization is not included.

Fertilization

The addition of nitrate, ammonium and organic matter before the crop is planted or as side-dressing is treated as a discrete event. Organic matter and any broadcast fertilizer is assumed to be uniformly mixed in the upper four soil layers. Side-dressing of banded fertilizer is placed in the soil cell dependent on where the cultivator shank runs.

LIMITATIONS OF THE MODEL

This first generation model of soil processes under growing row crops has several limitations in addition to lack of validation in several areas. A few of these limitations are discussed below. As needs arise and time and



CMPX ---- Component X, where X can be either sugar, cellulose, protein, lignin, or biomass

CNCMX --- Carbon/nitrogen ratio of component X

RDECX --- Rate of decomposition of component X

GRBIMX -- Growth rate of biomass (bacteria) due to feeding on component X

RPRN3X -- Rate of production of NH_3

RCON3X -- Rate of consumption of NH_3

RCONOX -- Rate of consumption of NO_3

GRHUM --- Growth rate of humus

HUM ----- Humus

Figure 7. Simplified systems dynamics flow chart of mineralization and nitrification processes (after Beek and Frissel, 1973).

effort permit, refinements and additions will be made.

Very few data are available on root growth which are amenable to inclusion in a quantitative simulation effort. Quantitative preferences for direction of growth, specific growth rates as dependent on age, temperature, water, nutrients and gaseous conditions, sloughing rates, etc., are not known in sufficient detail. We have therefore used the assumptions described above. Soil profiles which are homogeneous with respect to bulk density, water characteristics, and mechanical impedance are not realistic in most field conditions.

Data on water permeability of roots grown in soil as affected by age are unknown. Uptake of water as dependent on rooting density, root permeability and soil water conditions has not been quantified. The form and amount of nitrogen uptake by the transpiration stream are unknown.

More efficient methods of determining the capillary redistribution of water can be found. The lack of such methods is a very serious limitation in RHIZOS. Mechanisms of nitrate movement should be evaluated for possible inclusion.

Soil temperature predictions under a growing crop can be improved. Simulation of nitrogen processes can probably be refined.

Among the most feasible additions or refinements under the existing state of the art are

a. Mechanical impedance effects on root growth
b. Different boundary conditions on the soil water profile
c. Improvement in the method of calculating capillary redistribution of water and nitrate
d. Data on root growth as affected by temperature and soil water conditions
e. Nutrient effects on root growth
f. Oxygen availability and its effects on root growth.

All of these refinements can be added with relative ease to the logical structure described here.

IMPLEMENTATION

The concepts and assumptions described above for simulating certain soil processes under a growing row crop have been implemented into a Fortran computer program, using data for cotton. Rows 1 m wide, a root zone 1 m deep, and a 20 x 20 matrix of soil cells 5 cm x 5 cm are used.

Daily time steps are taken from emergence throughout the growing season in integrating the processes described above, with the exception of root water uptake and capillary flow. Stability requirements dictate that smaller time steps be used for these processes; we are currently using 0.1 day steps for capillary flow. Uptake occurs during half of the steps.

The major input requirements are separated for description purposes into initialization data; variables, which fluctuate daily; parameters, constant for the season; and relationships between pairs of variables.

Initialization

At emergence the one-dimensional soil temperature and the two-dimensional water content profiles must be supplied. The residual nitrate and ammonium nitrogen and organic matter contents separated into the components protein, sugar, cellulose, and lignin are also required. The root weight distribution by soil cell, must be specified.

Variables

The required daily weather variables are maximum and minimum air temperatures, rainfall, incident solar radiation, and average wind speed. Daily increments of carbohydrate available for root growth and the fraction of incoming radiation intercepted by the canopy are required from an above-ground simulator or other source. The amount, placement position, fraction nitrate and ammonium, and day of application of fertilizer are also needed.

Parameters

1. Field capacity (volumetric fraction) by layer.
2. Daylength or latitude of the field location, from which daylength can be calculated.
3. Albedo of canopy and soil.
4. Upper limit of stage I drying of the soil (See Ritchie, 1972).
5. Several specific rates, coefficients, and fractions used in mineralization and nitrification (See Beek and Frissel, 1973).
6. Sloughing factor for roots.
7. Geotropism factor for inducing downward root growth.
8. Threshold root weight for crossing of a soil cell by roots.

Relationships

1. Soil water diffusivity as a function of water content.
2. Reduction factor for transpiration. Currently used as an empirical function of radiation, temperature, and soil water potential.
3. Reduction factor for decomposition of organic matter due to temperature.
4. Reduction factor for decomposition of organic matter due to moisture content.
5. Water stress factor for calculating potential root growth. Currently used as a function of net radiation, soil water potential, and soil temperature.
6. Temperature effect on potential root growth.

VALIDATION

Three Soil-Plant-Atmosphere Research (SPAR) units (see Figure 8) have been installed at the Coastal Plains Soil and Water Conservation Research Center at Florence, South Carolina, for the specific purpose of refining and validating RHIZOS. Steel soil bins 1 m deep x 1/2 x 2 m were filled with air-dry Cecil sandy loam topsoil, vibrated and wetted for compaction. Two rows of cotton (Stoneville 213 var.) 1/2 m long x 1 m row spacing were planted on May 27, 1975. Fertilizers were banded 10 cm from the row and 12 cm below the soil surface at the following rates: 100 kg/ha N, 25 kg/ha P, 55 kg/ha K, 34 kg/ha Mg and trace B. Lime was applied at a rate of 5 mt/ha according to soil test results and was uniformly mixed in the upper 30 cm of soil. Irrigation was accomplished through 13 1/2 m pieces of Viaflo porous tube spaced 15 cm apart and installed about 2 cm deep. The soil surface was covered by plastic sheet to decrease CO_2 transfer between soil and atmosphere. Atmospheric carbon dioxide concentration of 600 ppm was maintained from 72 days after emergence.

Acrylic chambers 1/2 m x 2 m x 1 1/2 m tall were fastened to the top of the steel bins so that temperature and humidity could be maintained by a 19,000 BTU air conditioner and 5.8 KW electric heaters through an air circulating system. Carbon dioxide was also metered and controlled as will be described elsewhere.

Tensiometers were placed at the three sampling depths under each crop row as indicated in Figure 8 and midway between the row and were read daily to obtain the two-dimensional capillary water potential distribution. Soil temperature was also recorded. Other data were also obtained above ground, as will be reported in more detail elsewhere: node and flower counts twice

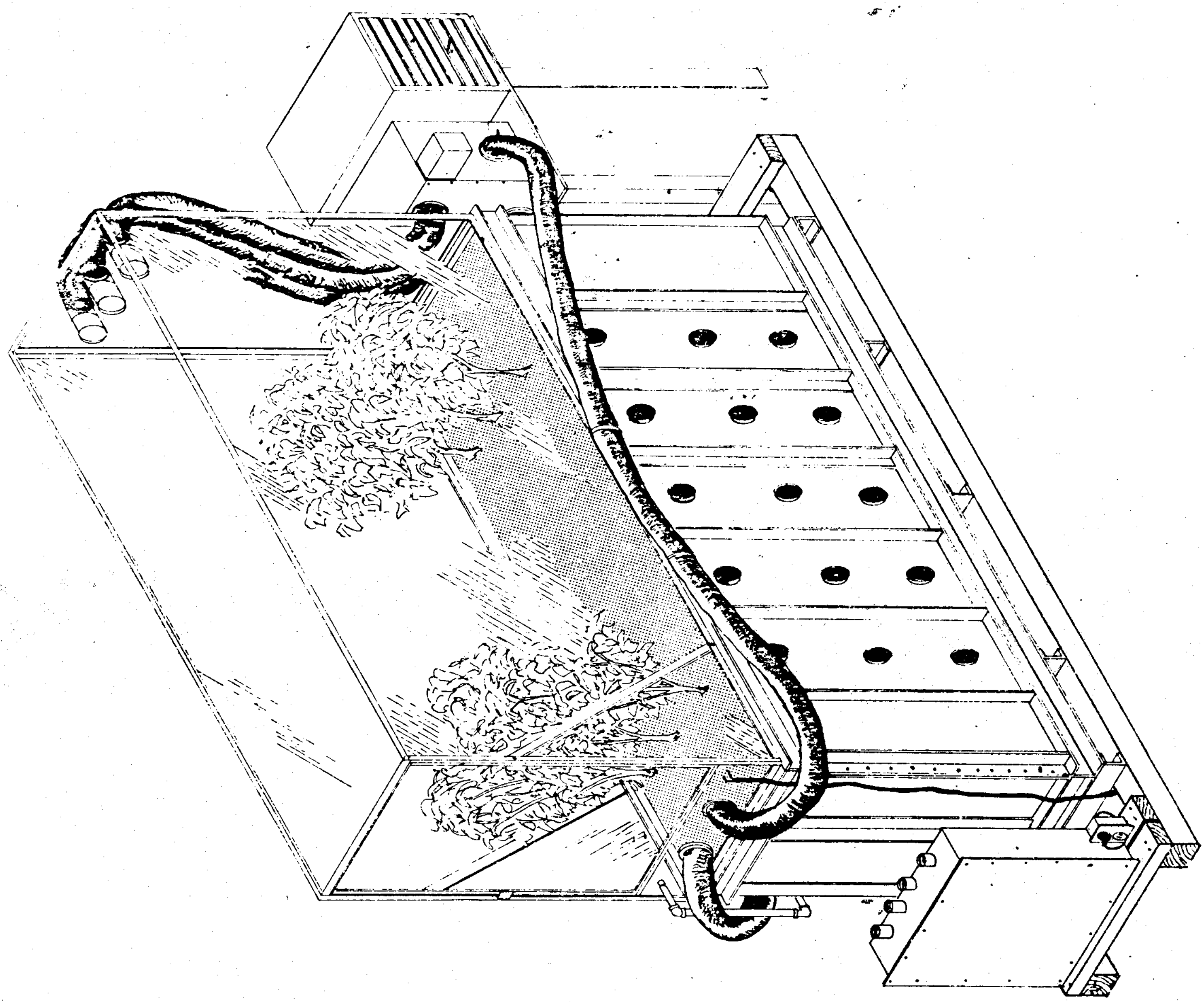


Figure 8. Soil-Plant-Atmosphere Research (SPAR) unit.

weekly, leaf area, and plant heights. Photosynthesis and transpiration were also determined at 15-minute intervals.

Core samples of soil were taken periodically for determination of root distribution. Figure 9 shows the grid used for selecting locations for obtaining the soil cores. On each sampling date, 2.5 cm thin wall conduit was used to take a full-depth core from each of the 18 positions perpendicular to the rows, at a randomly selected one of nine positions parallel to the rows. Thus a complete two-dimensional profile of root density was obtained.

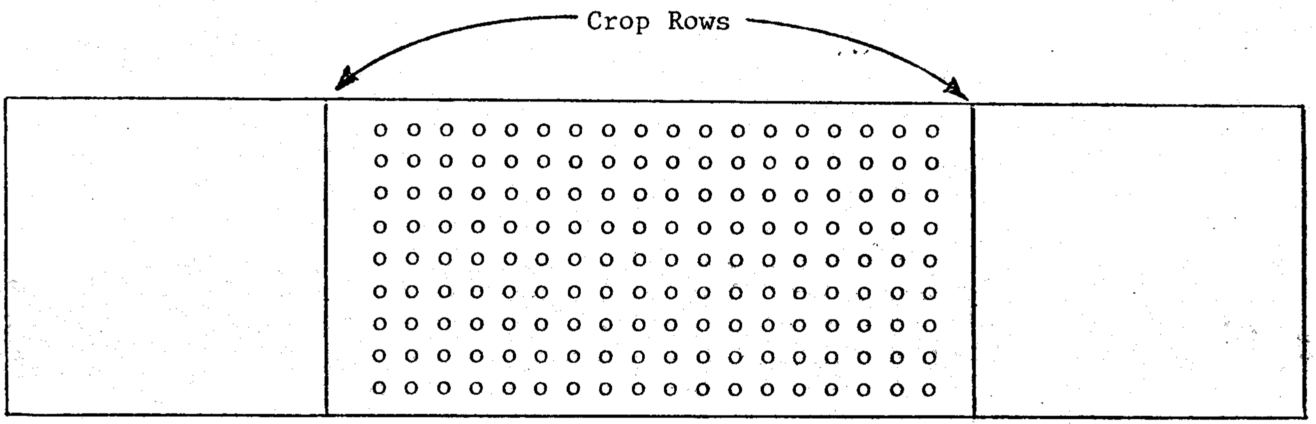


Figure 9. Plan view of root sampling layout.

RESULTS

Figure 10 indicates the relative root distribution measured in the profile 81 days after emergence. No data were obtained directly under the rows, i.e. columns 1 and 20. The digits in the matrix indicate the weight class of the fresh weight of the roots over the corresponding 5-cm length of core sample as defined by the legend. Thus the "6" appearing in column 4, layer 3, indicates that 0.032-0.064 gm fresh weight of roots were obtained in the core sample, centered 17.5 cm from the left row, between 10 and 15 cm deep. Failure to retrieve samples from the deeper layers was due to the soil being either too loose or too wet. A higher density of roots was observed near the plane under the rows and in the upper 20-25 cm of soil. Computer simulations show simular patterns, but do not indicate roots to be as prevalent in the deeper zone midway between the rows. No correlation is apparent between the 3's, 4's, and 5's in layers 16 and 17 and the sample position with respect to an end wall.

Other experimental data are persented elsewhere (Lambert at al, 1975, Phene et al, 1976).

RHIZOS has been included in GOSSYM (for Gossypium simulator), a simulator of cotton growth and yield which is sensitive to water and nitrate within the soil profile. Typical maps of water content, nitrate content, and root concentration in the soil profile as predicted by the computer simulation for day 81 are presented as Figures 11, 12, and 13, respectively. Such maps can be generated for any desired day.

A comparison of the actual and predicted total root weight in the soil profile is shown in Figure 14.

It must be emphasized at this point that both RHIZOS and GOSSYM are still in the verification and validation stages. Several possible reasons exist for discrepancies between the actual and predicted total root weights during the growing season.

The relative spatial distribution in space of water and roots is not yet entirely correct. Therefore the water and nitrogen stresses on the crop is not exactly as simulated and so total growth of the crop is not simulated exactly.

Death and sloughing of roots is essentially an unknown, especially as they are affected by age, temperature, moisture content, and oxygen concentration.

ROOTS IN EACH CELL,
EXPERIMENTAL DATA

DAY 81

UNITS - GM FW

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1		6	3	5	5	5	5	6	3	4	3	4	5	5	5	5	7	5	2	
2		7	5	6	5	6	6	6	5	6	6	5	5	7	7	6	7	7	7	
3		8	6	6	4	6	6	5	6	7	6	6	5	7	6	7	6	5	6	
4		5	6	6	5	4	5	5	5	6	5	5	5	6	6	6	6	6	5	
5		6	5	4	5	5	5	6	5	5	5	5	5	6	5	5	6	5	5	
6		6	6	5	5	5	7	5	5	6	4	5	5	6	5	4	6	4	5	
7		4	6	5	5	5	5	5	5	6	5	6	5	5	5	5	5	6	5	
8		4	5	6	4	4	4	6	6	6	6	6	6	5	4	5	5	7	6	
9		4	5	3	5	3	4	4	6	5	6	6	5	5	5	5	5	6	6	
10		5	5	6	5	5	4	3	6	5	6	5	5	3	5	5	6	6	6	
11		6	5	3	6	6	7	6	4	5	7	4	5	5	5	5	6	6	5	
12		7	6	5	5	4	7	7	4	4	6	6	6	5	6	6	5	7	6	
13		5	6	6	6	6	6	7	6	5	7	4	6	5	5	5	6	6	5	
14		6	5	5	5	5	-	-	5	6	6	-	5	4	7	5	6	-	2	
15		0	2	-	0	-	-	-	0	-	-	-	-	-	0	-	4	-	-	
16		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
17		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
18																				
19																				
20																				

LEGEND

			< = 0.0
0.0	<	0	< = 0.001
0.001	<	1	< = 0.002
0.002	<	2	< = 0.004
0.004	<	3	< = 0.008
0.008	<	4	< = 0.016
0.016	<	5	< = 0.032
0.032	<	6	< = 0.064
0.064	<	7	< = 0.128
0.128	<	8	< = 0.256
0.256	<	9	< = 0.512
0.512	<	*	

- sample not retrieved

TOTAL = 9.109 GM FRESH WEIGHT

Figure 10. Relative root distribution in soil profile as measured 81 days after emergence of cotton.

VOLUMETRIC WATER CONTENT OF SOIL
AT THE END OF MAIN

DAY 81

UNITS - CM**3/CM**3 SOIL

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2	7	7	7	7	8	8	8	8	8	8	8	6	8	8	8	8	7	7	7	7
3	6	6	6	7	7	7	8	8	8	8	8	8	8	8	7	7	7	6	6	6
4	6	6	6	6	6	7	8	8	8	8	8	8	8	8	7	6	6	6	6	6
5	5	5	5	6	6	6	7	8	8	8	8	8	8	7	6	6	6	5	5	5
6	5	5	5	5	6	6	7	8	8	8	8	8	8	7	6	6	5	5	5	5
7	5	5	5	5	6	6	7	8	8	8	8	8	8	7	6	6	5	5	5	5
8	5	5	5	6	6	7	8	8	8	8	8	8	8	8	7	6	6	5	5	5
9	5	5	5	6	7	7	8	8	8	8	8	8	8	8	7	7	6	5	5	5
10	5	5	6	6	7	8	8	8	8	8	8	8	8	8	8	7	6	6	5	5
11	6	6	6	7	8	8	8	8	8	8	8	8	8	8	8	8	7	6	6	6
12	6	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	7	7	6
13	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	7	7
14	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	7
15	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
16	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
17	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
18	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
19	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
20	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8

TOTAL = 394.7332 MM WATER

LEGEND

			<=	0.0
0.0	<	0	<=	0.0500
0.0500	<	1	<=	0.1000
0.1000	<	2	<=	0.1500
0.1500	<	3	<=	0.2000
0.2000	<	4	<=	0.2500
0.2500	<	5	<=	0.3000
0.3000	<	6	<=	0.3500
0.3500	<	7	<=	0.4000
0.4000	<	8	<=	0.4500
0.4500	<	9	<=	0.5000
0.5000	<	*		

Figure 11. Volumetric water content of a soil profile under growing cotton as predicted by computer simulation.

VOLUMETRIC NITRATE CONTENT OF SOIL
AT THE END OF MAIN

DAY 81

UNITS - MG/N PER CM**3

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	0	0	0	0	0									0	0	0	0	0	0
2																				
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5																				
6																				
7	1	2	*															*	2	1
8	2	5	*	1	0	0	0	0					0	0	0	0	1	*	5	2
9	1	4	*	3	2	2	2	1	1	1	1	1	1	2	2	2	3	*	4	1
10	0	1	*	4	4	4	4	3	3	3	3	3	3	4	4	4	4	*	1	0
11	0	0	6	4	5	5	5	5	5	5	5	5	5	5	5	5	4	6	0	0
12	0	0	1	2	4	4	5	5	5	5	5	5	5	5	4	4	2	1	0	0
13	0	0	0	0	2	2	3	3	4	4	4	4	3	3	2	2	0	0	0	0
14	0	0	0	0	0	1	1	2	2	2	2	2	2	1	1	0	0	0	0	0
15	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TOTAL = 171.7330 MG N

LEGEND

			<=	0.0
0.0	<	0	<=	0.0100
0.0100	<	1	<=	0.0200
0.0200	<	2	<=	0.0300
0.0300	<	3	<=	0.0400
0.0400	<	4	<=	0.0500
0.0500	<	5	<=	0.0600
0.0600	<	6	<=	0.0700
0.0700	<	7	<=	0.0800
0.0800	<	8	<=	0.0900
0.0900	<	9	<=	0.1000
0.1000	<	*		

Figure 12. Volumetric nitrate content of soil profile under growing cotton as predicted by computer simulation.

ROOTS IN EACH CELL, TOTAL
AT THE END OF RUTGRO

DAY 81

UNITS - G/CM**3 SOIL

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	2	2	2	2	1	0														
2	4	4	3	3	2	2	2	0	0											
3	4	4	5	4	4	3	2	2	0	0										
4	4	4	4	4	4	3	2	2	0	0										
5	5	4	4	3	4	3	2	2	0	0										
6	5	5	4	3	3	3	2	1	0											
7	5	5	4	4	3	2	2	0	0											
8	4	5	4	3	2	2	2	0												
9	4	4	3	3	2	2	1	0												
10	4	3	3	2	2	1	0													
11	3	3	2	2	2	0	0													
12	2	2	2	2	0	0														
13	2	2	2	1	0															
14	2	2	1	0																
15	1	1	0	0																
16	0	0	0																	
17	C																			
18																				
19																				
20																				

LEGEND

		<=	0.0
0.0	< 0	<=	0.0001
0.0001	< 1	<=	0.0005
0.0005	< 2	<=	0.0050
0.0050	< 3	<=	0.0100
0.0100	< 4	<=	0.0150
0.0150	< 5	<=	0.0200
0.0200	< 6	<=	0.0250
0.0250	< 7	<=	0.0300
0.0300	< 8	<=	0.0350
0.0350	< 9	<=	0.0400
0.0400	< *		

TOTAL = 0.5988 GM. DRY WEIGHT

Figure 13. Root concentration in the soil under growing cotton as predicted by computer simulation.

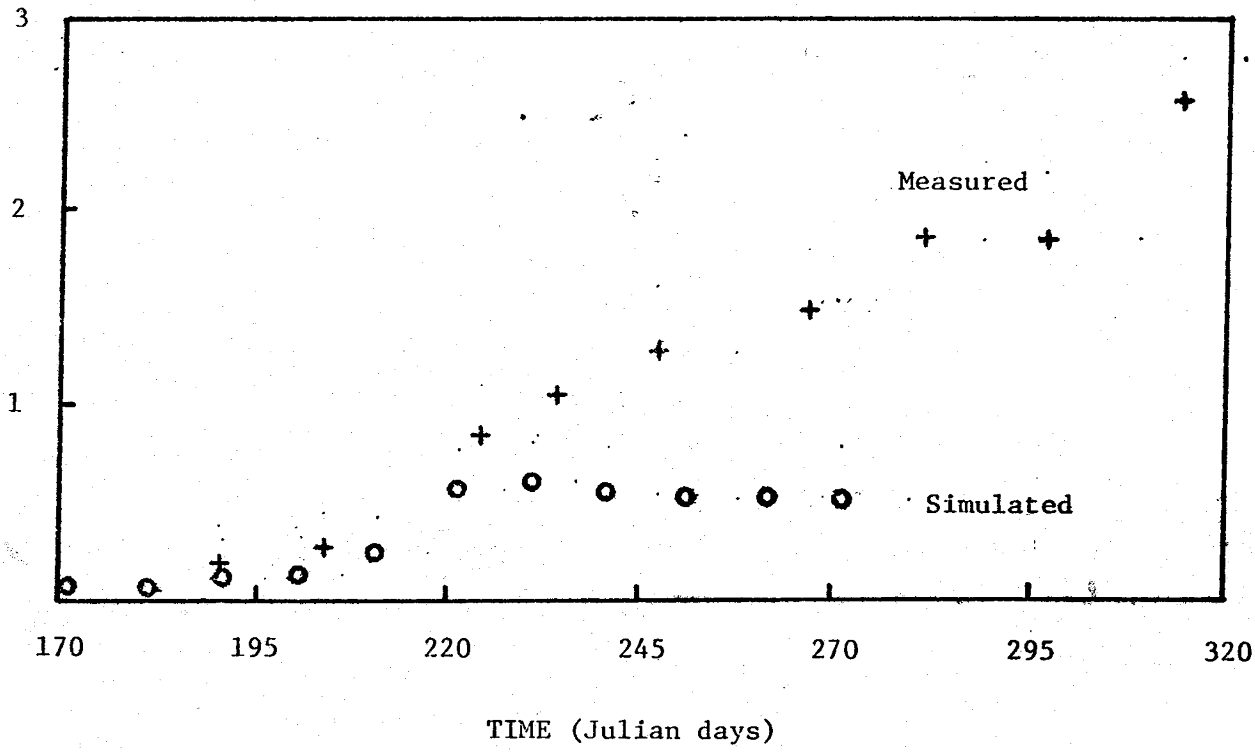


Figure 14. Actual and predicted total root weight in the soil profile under growing cotton at 600 ppm CO_2.

Our sampling technique collects only a small sample of the roots in the profile. Other observations indicate that roots are stochastically placed in the profile and therefore a more intensive sampling method is needed. Ideally, a non-destructive method would be much more amenable to our use.

CONCLUSIONS

As a result of the development, verification, and preliminary validation of RHIZOS, a simulator of the rhizosphere including root growth and water and nitrate uptake, the following conclusions are drawn:

1. A dynamic simulation of a living agricultural system requires a multidisciplinary team approach.
2. Very serious gaps in our knowledge about even the simplest systems exist. Building a simulator is the most direct and sure method of determining what research would be most profitable.
3. Root distribution is stochastic as well as responsive to water, temperature, impedance, and possibly, nutrient availability.
4. Research is needed on methods of calculating water movement within soil, with emphasis on techniques for utilizing longer time steps.
5. Validation efforts for simulation models of living agricultural systems are expensive. They require significant allocation of capital, technicians, instrumentation, and professional manpower.

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